Heat-Transfer Measurement Capabilities in the NASA Ames Hypervelocity Free Flight Aerodynamic Facility

THERMAL & FLUIDS ANALYSIS WORKSHOP

GSFC · 2015

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Outline

- Introduction
  - Background
  - The Hypervelocity Free Flight Aerodynamic Facility (HFFAF)
  - Thermal Imaging
- Forebody Measurement Approach
  - Example Results
- Afterbody Measurement Approach
  - Example Results
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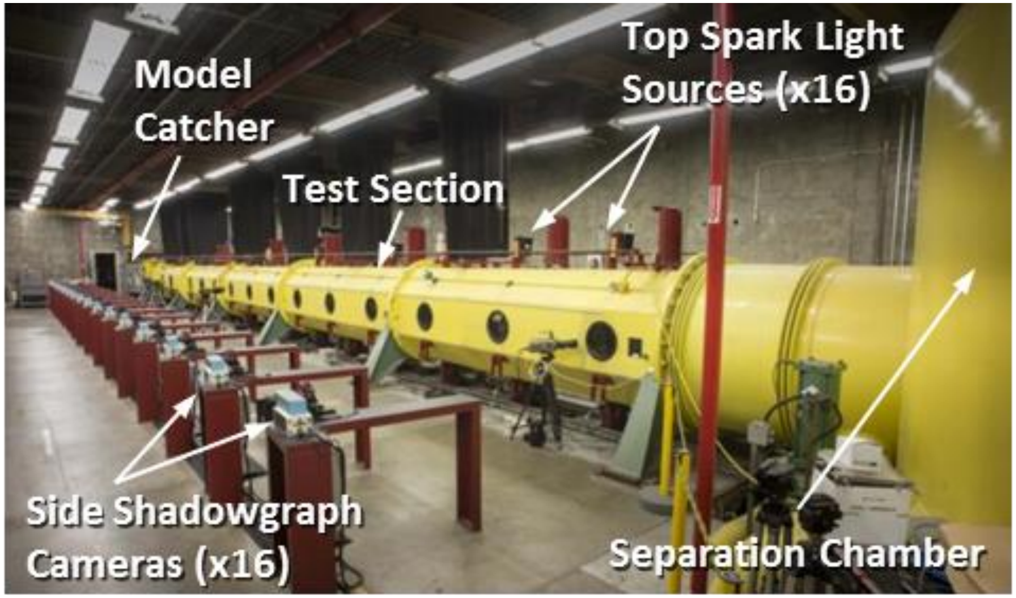
Introduction

- Convective heat transfer measurements on model entry vehicles obtained in hypersonic ground-test facilities
  - Provide data necessary to validate entry-environment simulation tools, and to anchor ground-to-flight traceability
  - Allows exploration of the impact of configuration (geometry and/or surface roughness) and test condition (Mach number, Reynolds number, test gas composition) on aerodynamic heating
- The Hypervelocity Free Flight Aerodynamic Facility (HFFAF) allows
  - Testing in well-defined, quiescent, “freestream”
  - Testing with no model support interference on the flow
  - Independent control of Mach number and Reynolds number
  - Testing in gases other than air
  - Ability to closely match key aerodynamic parameters of full-scale flight in many cases

Introduction

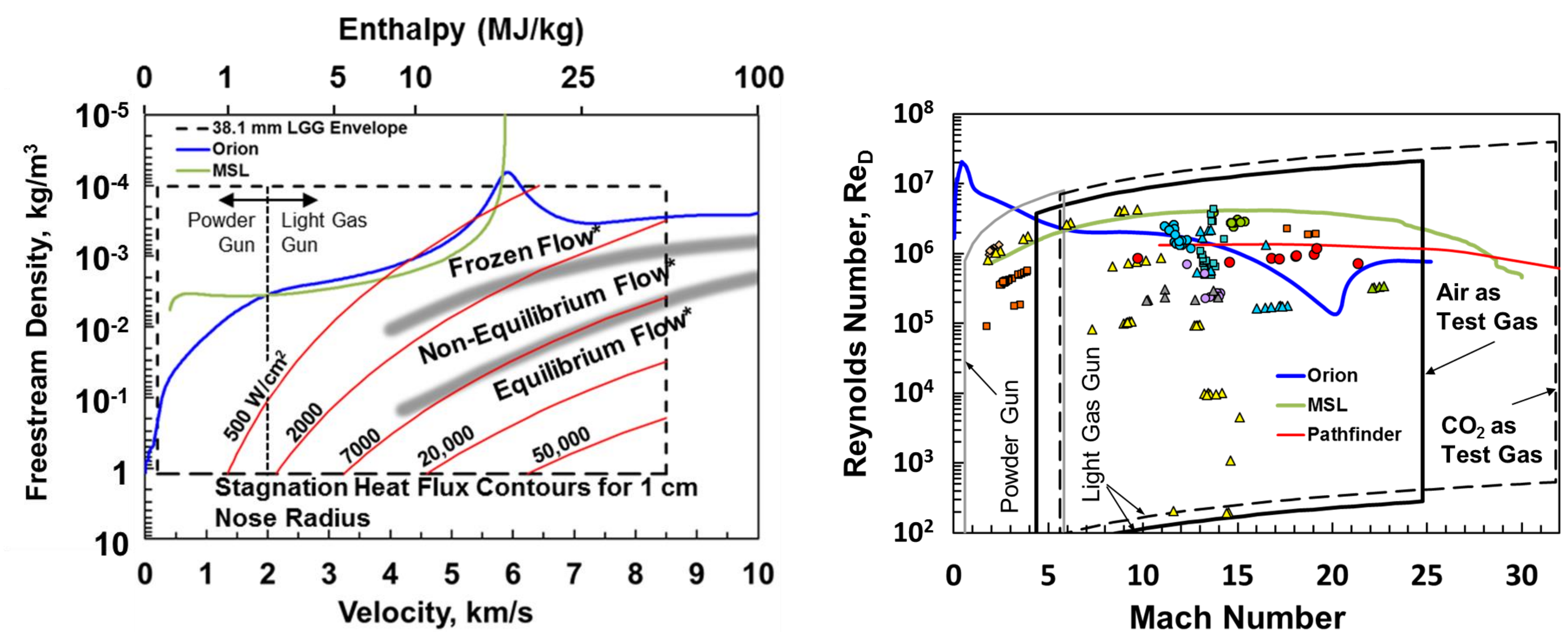
- The Hypervelocity Free Flight Aerodynamic Facility (HFFAF)
  - Gun-launched, free-flight projectiles
    - Largest hypervelocity launcher 38.1 mm bore (speeds approaching 8.5 km/s)
    - Largest launcher 61 mm bore (speeds approaching 2.5 km/s)
  - Controlled-atmosphere test section with the capability to independently vary Mach number, Reynolds number, and test gas (Air, N_2, CO_2, Ar, H_2/He, etc.)
  - Developed during the Apollo era, every NASA entry capsule, from Apollo to the Low-Density Supersonic Decelerator (LDSD), has been tested in the facility



For additional information visit http://www.nasa.gov/centers/ames/thermophysics-facilities/ballistic-ranges

Introduction

- HFFAF Flight Simulation Envelope
  - (Left) In terms of facility parameters, model velocity and test section static gas density
  - (Right) In terms of Mach number and Freestream Reynolds number for a 2.5 cm diameter model



*Designates conditions necessary to produce non-equilibrium flow in the shock layer over a blunt body of 1 cm nose radius in the ballistic range (Sharma and Park, *J. Thermophysics*, Vol. 4, No. 2, April 1990)

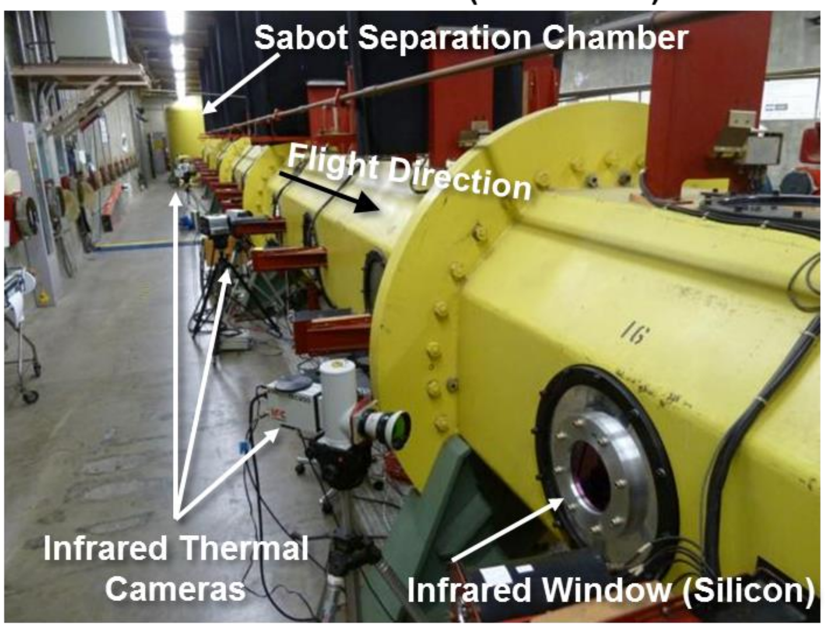
Introduction

- Heat transfer measurements on hypervelocity free-flight models using discrete sensors (thin-film gauges, calorimeters, thermocouples) is challenging
  - Models are small (< 38 mm diameter) and all data acquisition, data storage or transmission, and power systems hardware must fit inside the projectile
  - Models are subjected to extreme accelerations on launch (100,000 to 500,000 g)
- Thermal imaging allows global measurement of surface temperatures on projectiles, from which convective heat transfer rates can be inferred
  - Requires knowledge of the temperature-dependent thermophysical properties of the material from which the model is fabricated (conductivity, specific heat, and emissivity)

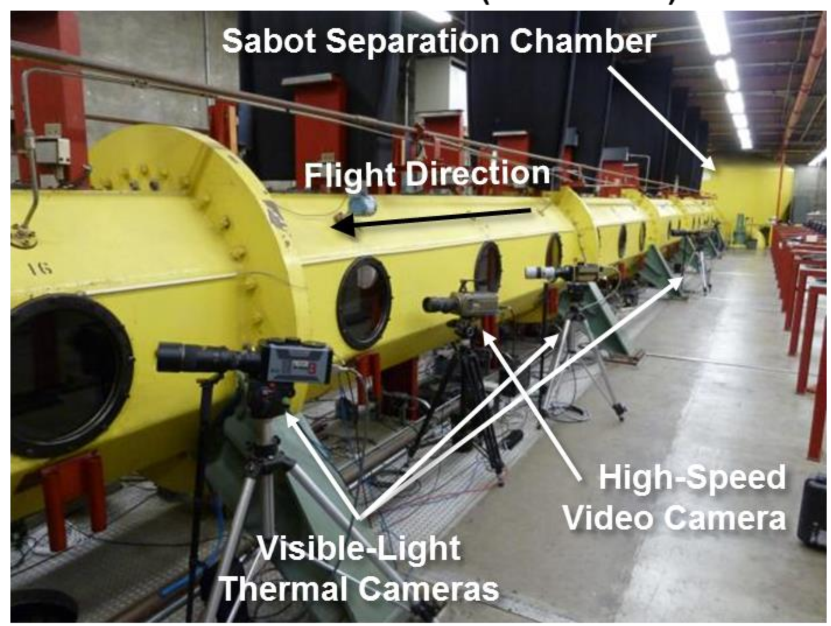
Introduction

- Thermography Instrumentation in the HFFAF
  - Midwave infrared (3 – 5 μm) for temperatures > 400 K
  - Visible-light cameras (0.53 – 0.86 μm) for temperature > 1000 K
- Test performance diagnostics cameras
  - High-speed digital video (30 – 80 kHz), visible-light imaging

HFFAF Test Section (North Side)

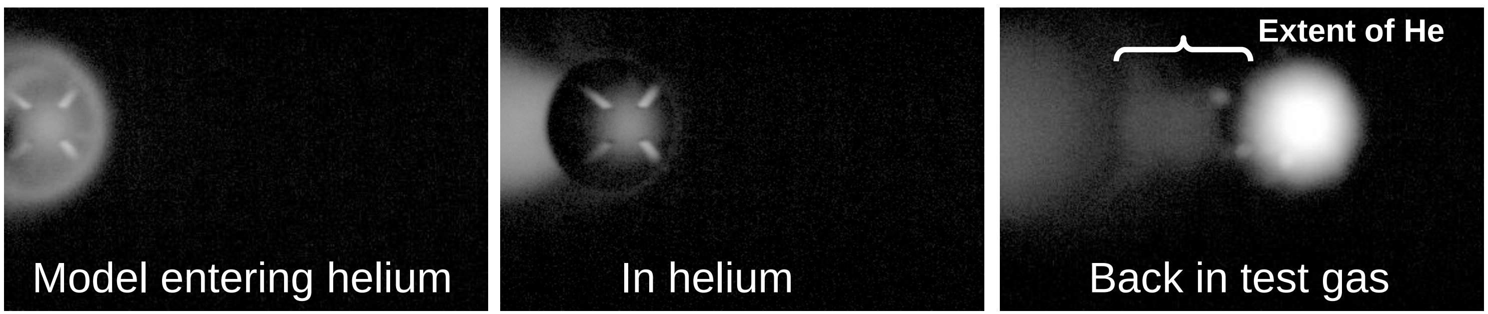


HFFAF Test Section (South Side)

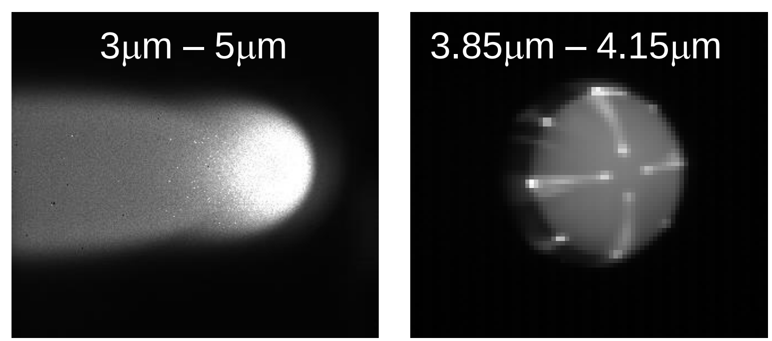


Introduction

- Hypervelocity projectiles are self-luminous. Radiation from the bow shock or wake will bias the measure of thermal radiation from the heated surface if not mitigated
  - In visible and IR wavelengths, bow shock radiation can be suppressed by flying through a local plume of helium

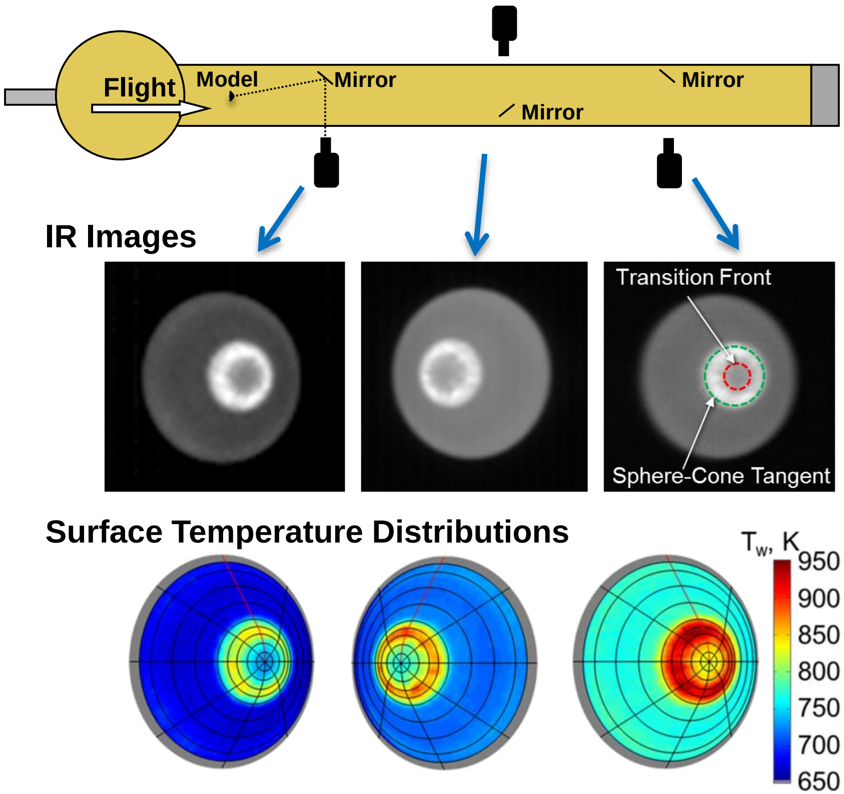


  - In midwave IR wavelengths, bow shock and wake radiation can be filtered out optically (practically no radiation in narrow band centered on 4 μm)



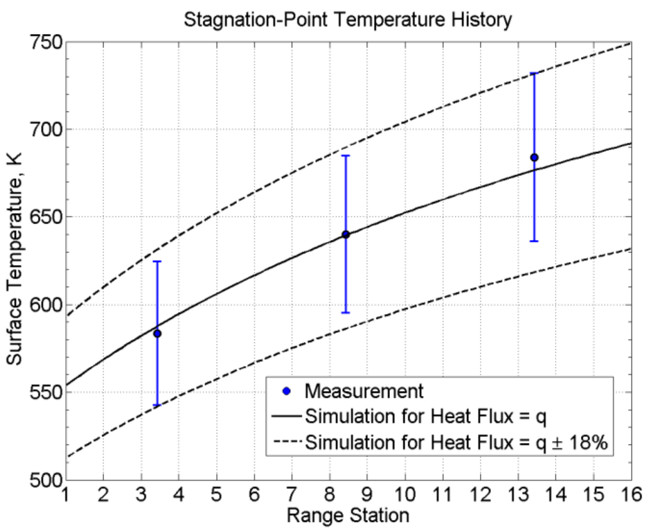
Forebody Measurement Approach

Example: 45º Sphere-Cone in Flight in HFFAF Test Section



Wilder, et al., AIAA-2014-0512

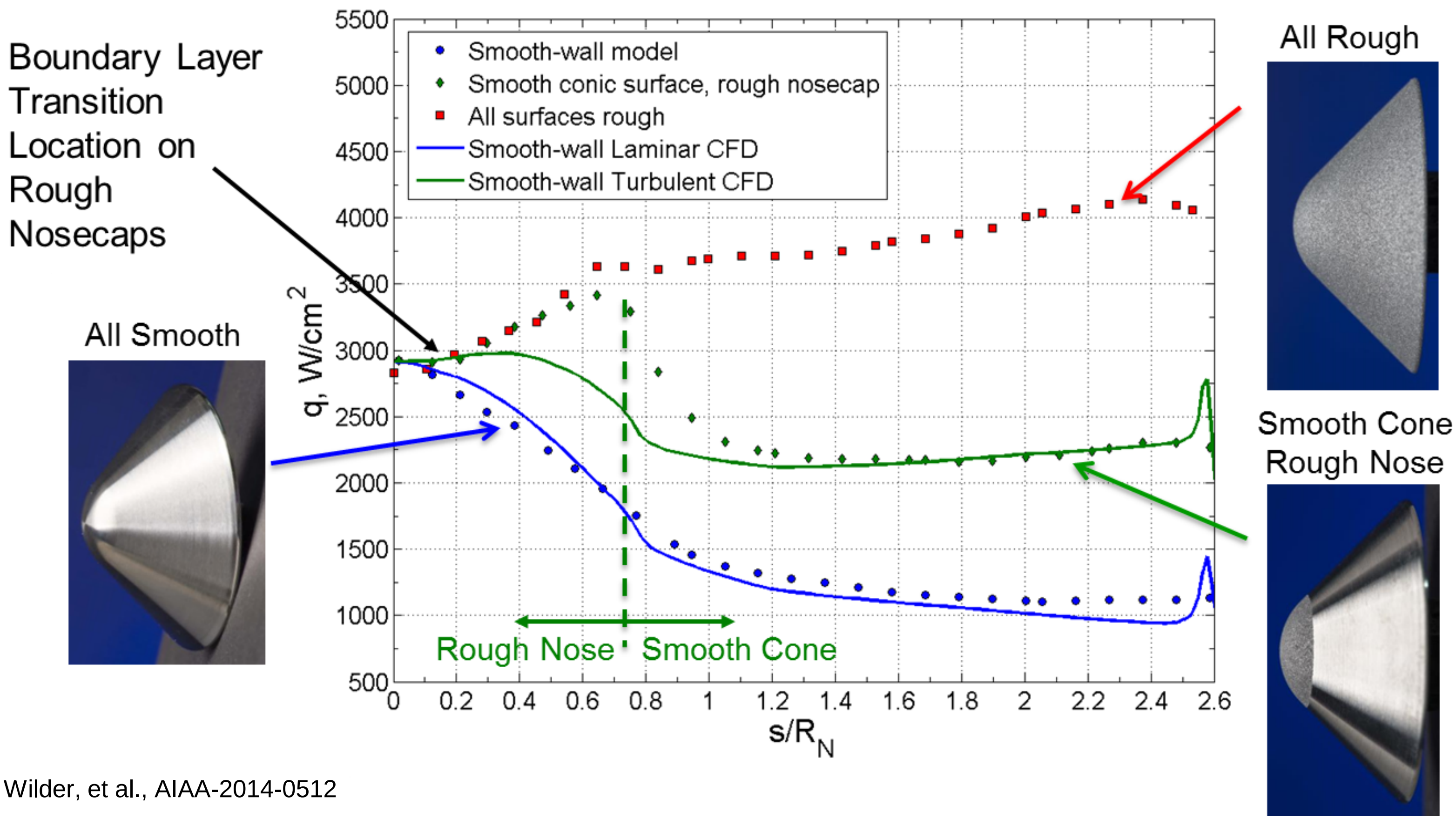
- Heat-transfer rate at each point on model determined by
  - Simulating temperature time history by solving 1D heat conduction for different convective heat flux boundary conditions
  - Find solution that best fits measured temperatures



Wilder, et al., AIAA-2011-3476

Forebody Measurement Approach

- Example: Effect of surface roughness on heat transfer
  - Mean convective heat-flux profiles on 45º sphere-cone models in air: R_N = 7.62 mm, V_0 = 3.0 km/s, P_∞ = 0.15 atm



Wilder, et al., AIAA-2014-0512

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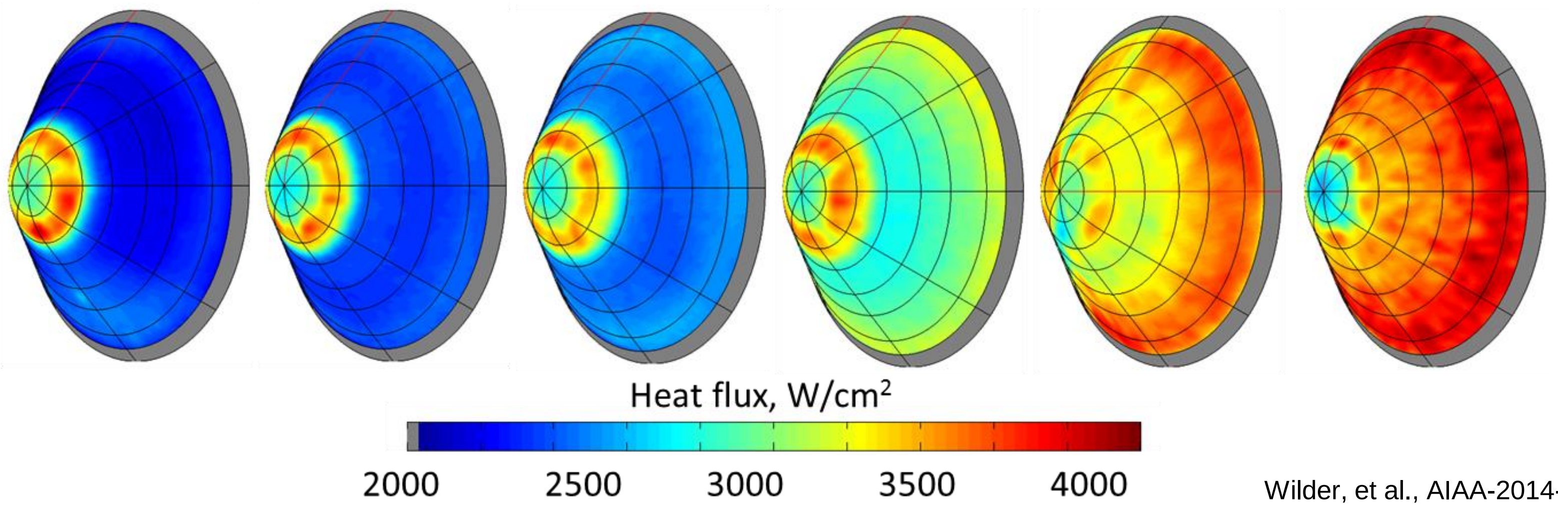
Increasing roughness height, k, relative to sublayer thickness, δ_s

k =	1.5 µm	3.2 µm	6.6 µm	10.2 µm	17.7 µm	23.6 µm
k/δ_s =	0.7	1.4	2.9	4.5	7.9	10.6
Re_k =	7	16	32	50	87	116



Wilder, et al., AIAA-2014-0512

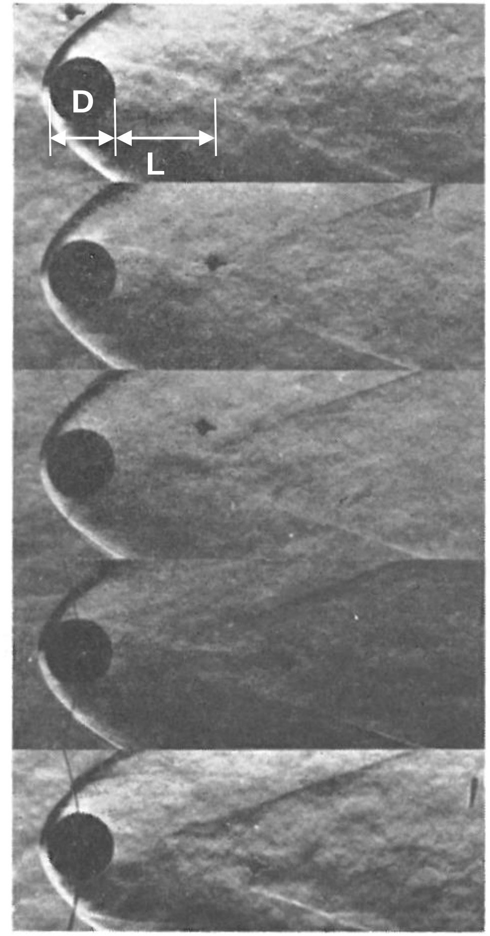
Afterbody Measurements

- Flight-test data, especially in non-terrestrial atmospheres, are rare
  - Limited afterbody data from Mars (Viking and Pathfinder) and Jupiter (Galileo)

- Interpretation of afterbody ground-test data obtained in wind tunnels are usually complicated by interference effects with the model support (or sting)
  - The presence of a single traverse vertical wire support noticeably altered the sphere separation region shape at 1.3 < M < 5*

- There are no sting effects in free-flight ballistic-range tests, but data acquisition poses challenges

Effect of Vertical Wire Support Diameter on Sphere Wakes: M = 3, Re_D = 2.2 x 10^5

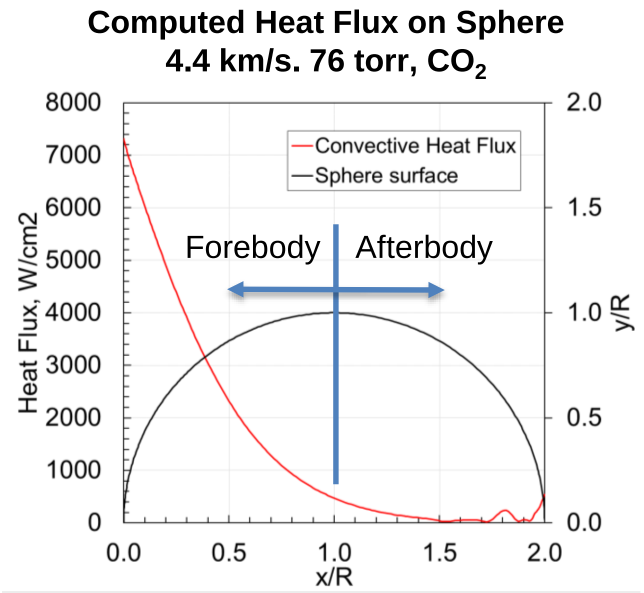


Wire diameter (in.)	Wake Length, L
0	1.56D
0.005	1.47D
0.010	1.37D
0.020	1.14D
0.040	0.77D

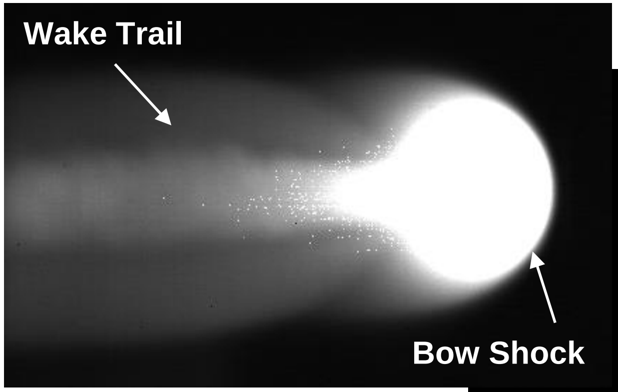
*Dayman, Jr., B., "Support Interference Effects on the Supersonic Wake," *AIAA Journal*, Vol. 1, No. 8, August 1963

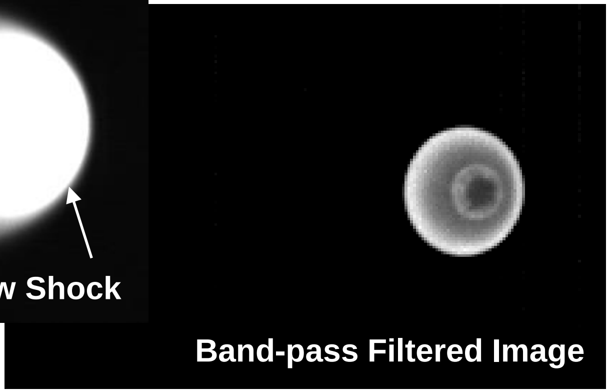
Afterbody Measurement Challenges

- Heat transfer rates on afterbodies are low, only a few percent of stagnation-point value



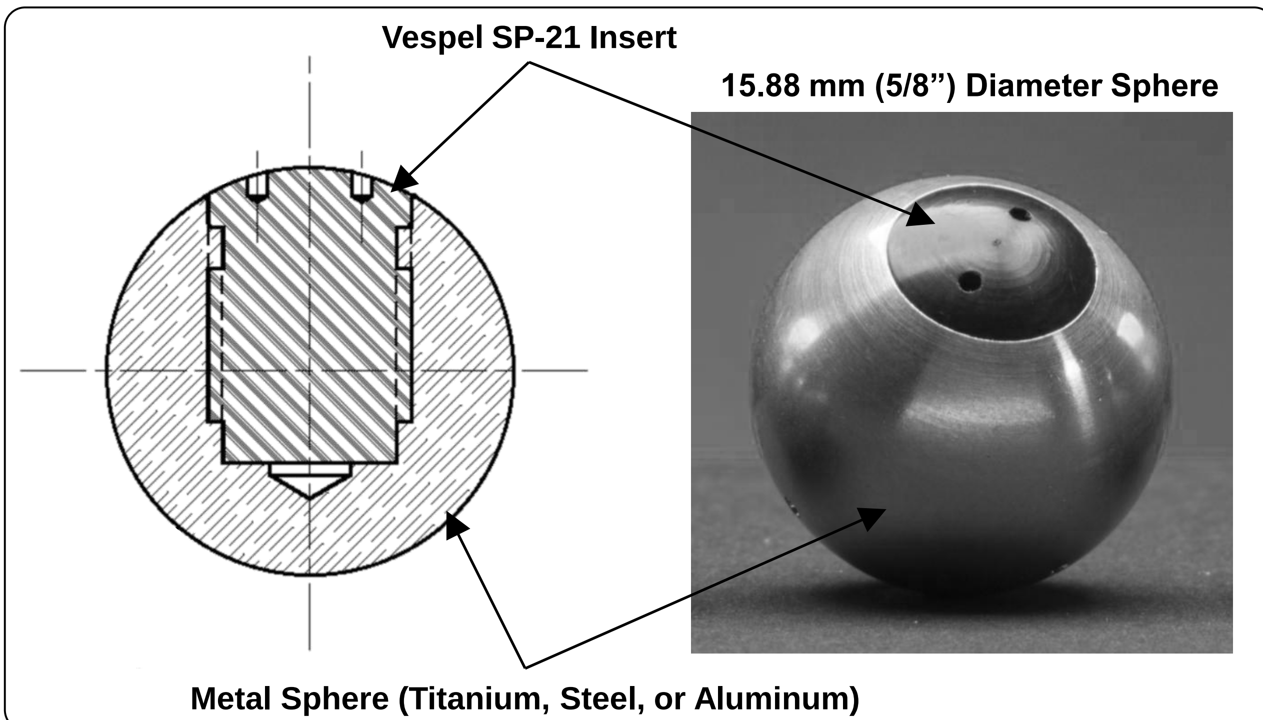
- The wake of hypersonic projectiles is self luminous
  - Wake radiation can be optically filtered from MWIR images
  - But filter also reduces the thermal radiation signal by 70% to 90%
  - Need materials that heat rapidly and re-radiate efficiently





Model Design Approach

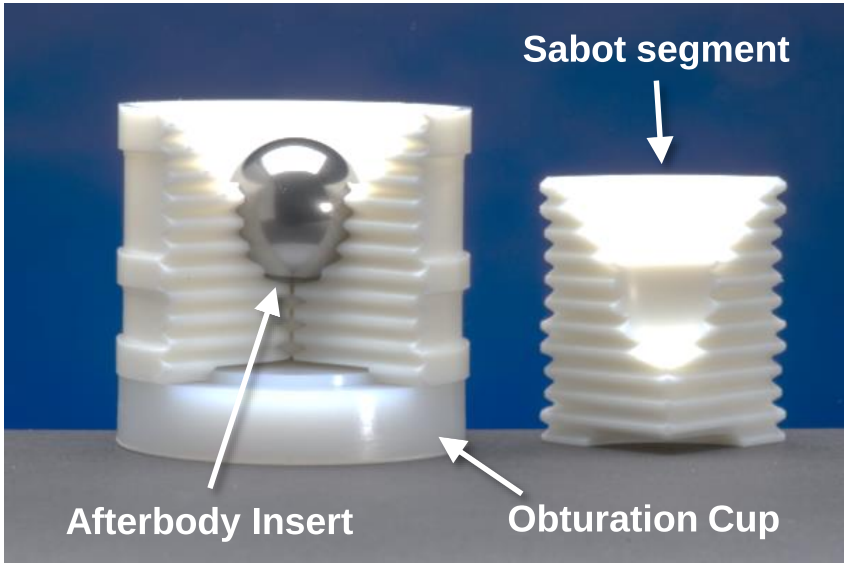
- Models fabricated in two parts:
  - Metal forebody to withstand high stagnation-point heat flux
  - Vespel afterbody insert for IR imaging on base
    - Dupont Vespel SP-21, low thermal conductivity polyimide matrix with graphite micro particles for high emissivity



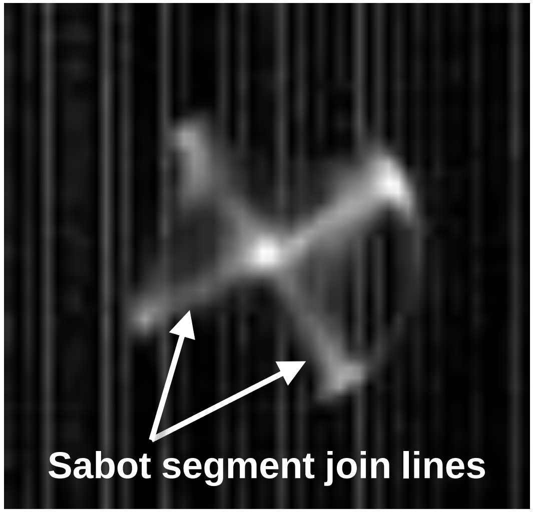
Launch Package Design

- For heat-transfer measurements, models must be shielded from heating by launch propellant gas
  - Obturation cup provides in-barrel gas seal, preventing gases from penetrating between sabot segments

Model and Sabot



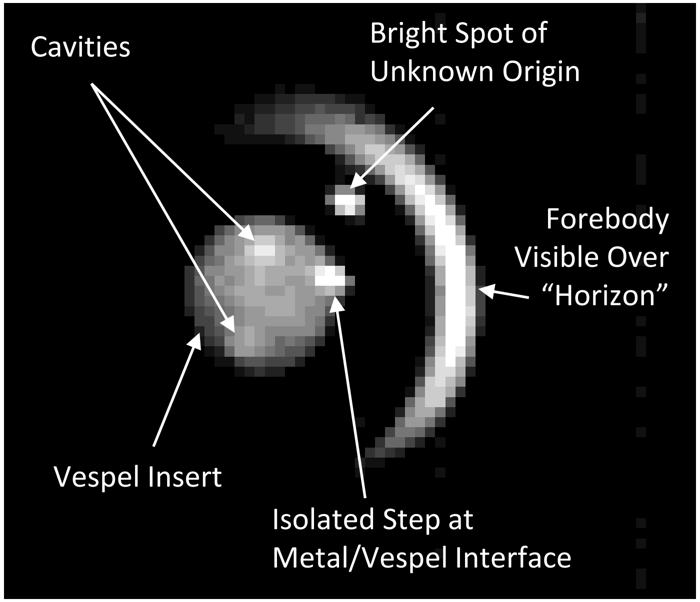
Hemisphere Launched without Obturator



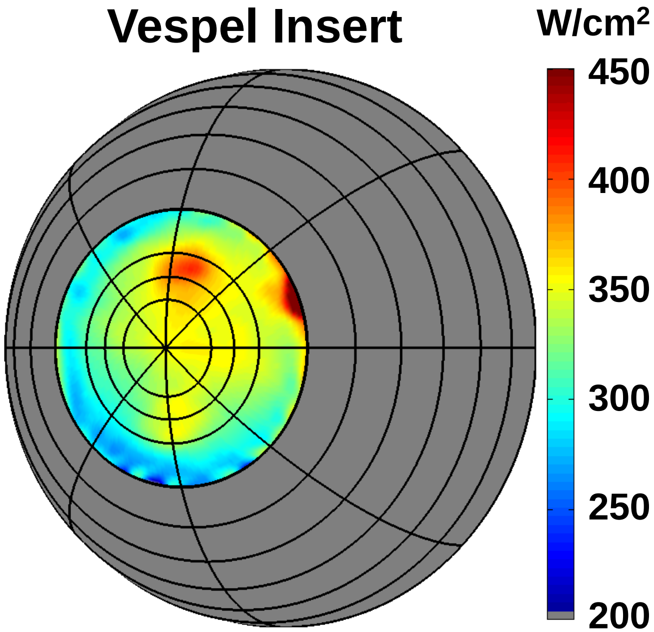
Afterbody Measurement Approach

- Example: Sphere with Vespel afterbody insert
  - Test gas = CO_2 at 76 Torr, V_0 = 4.44 km/s

Representative IR Image



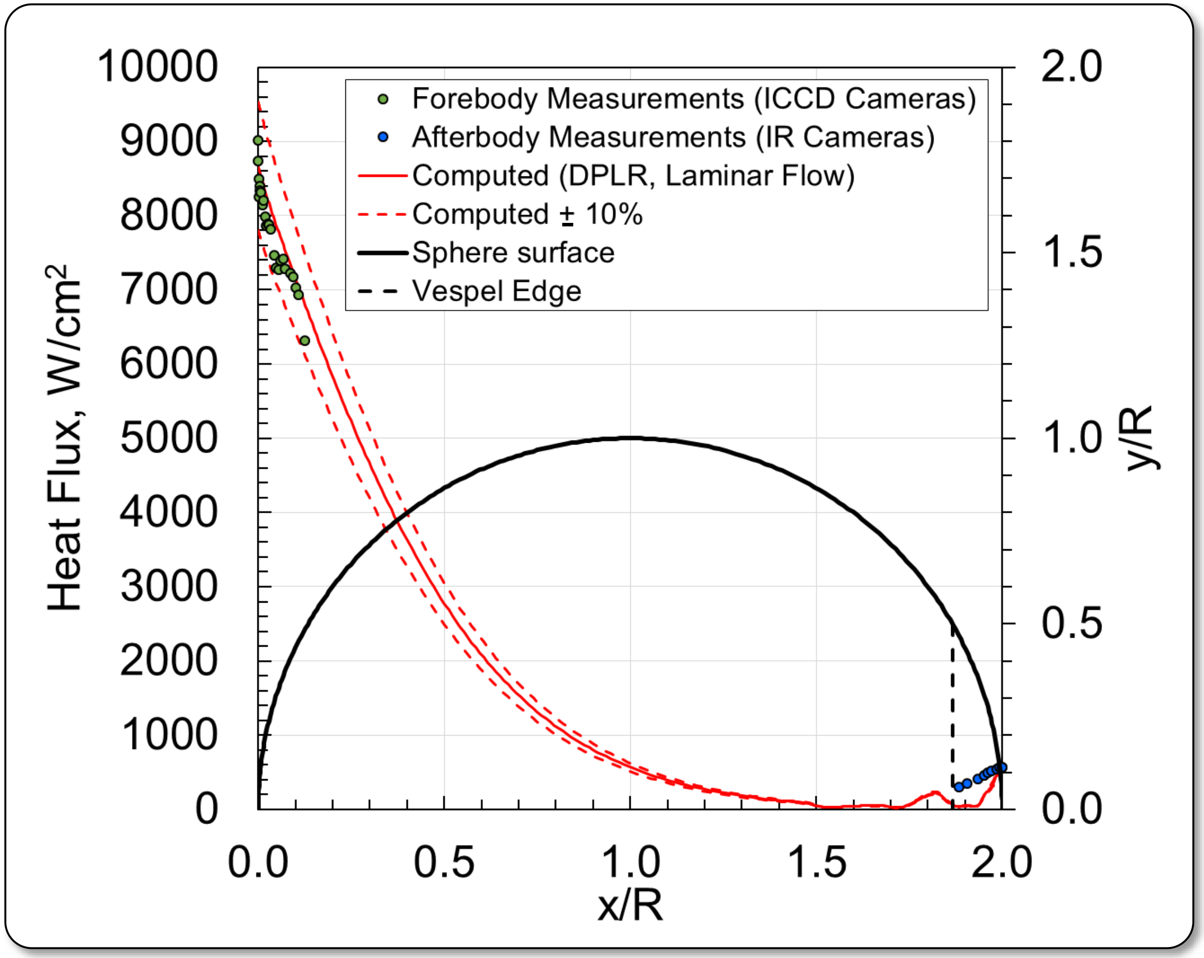
Heat-Flux Map on Vespel Insert



Wilder, et al., AIAA 2015-2966

Afterbody Measurement Approach

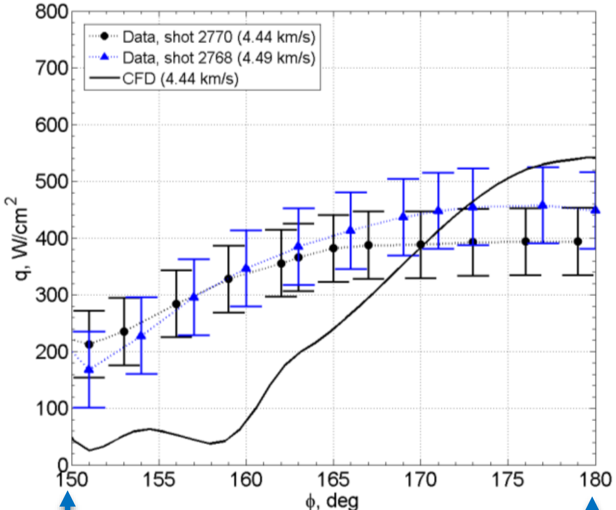
- Example: Stainless steel sphere with Vespel afterbody insert
  - Mean convective heat-flux profiles on sphere in CO_2
    R_N = 7.94 mm,
    V_0 = 4.86 km/s,
    P_∞ = 0.1 atm
    = 76 Torr
  - Axisymmetric, real-gas CFD solution



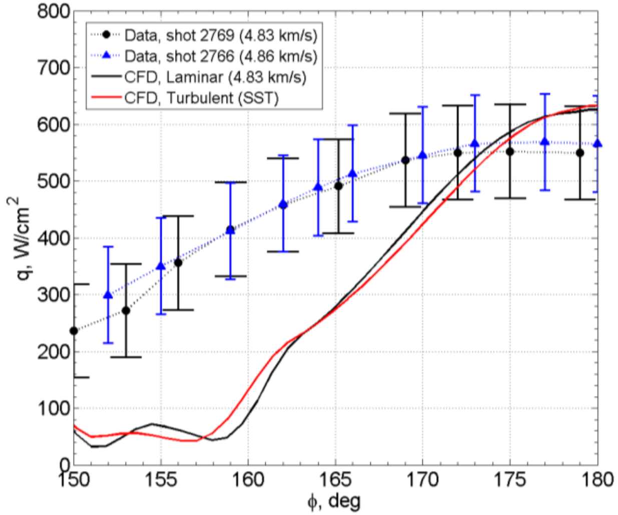
Results: Afterbody heat transfer, CO_2

Test gas = CO_2 at 76 Torr

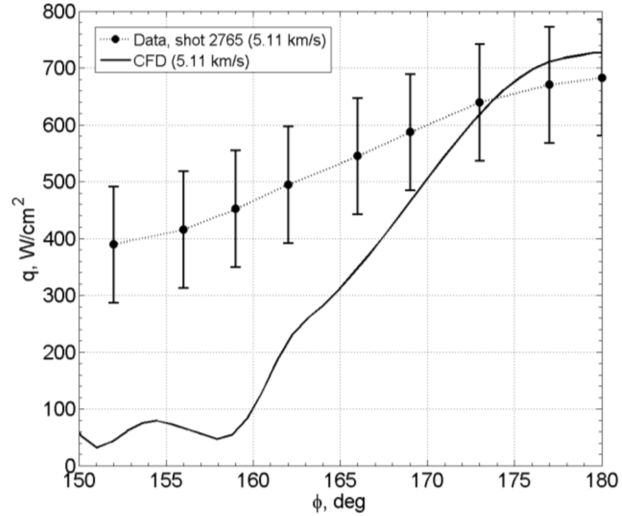
4.4 km/s



4.8 km/s



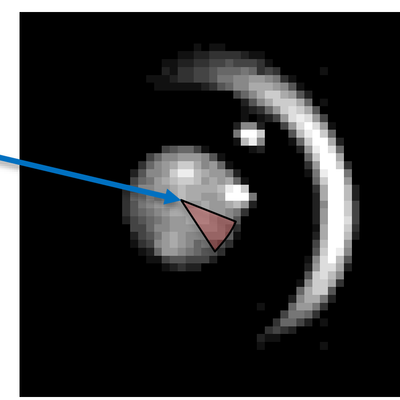
5.1 km/s



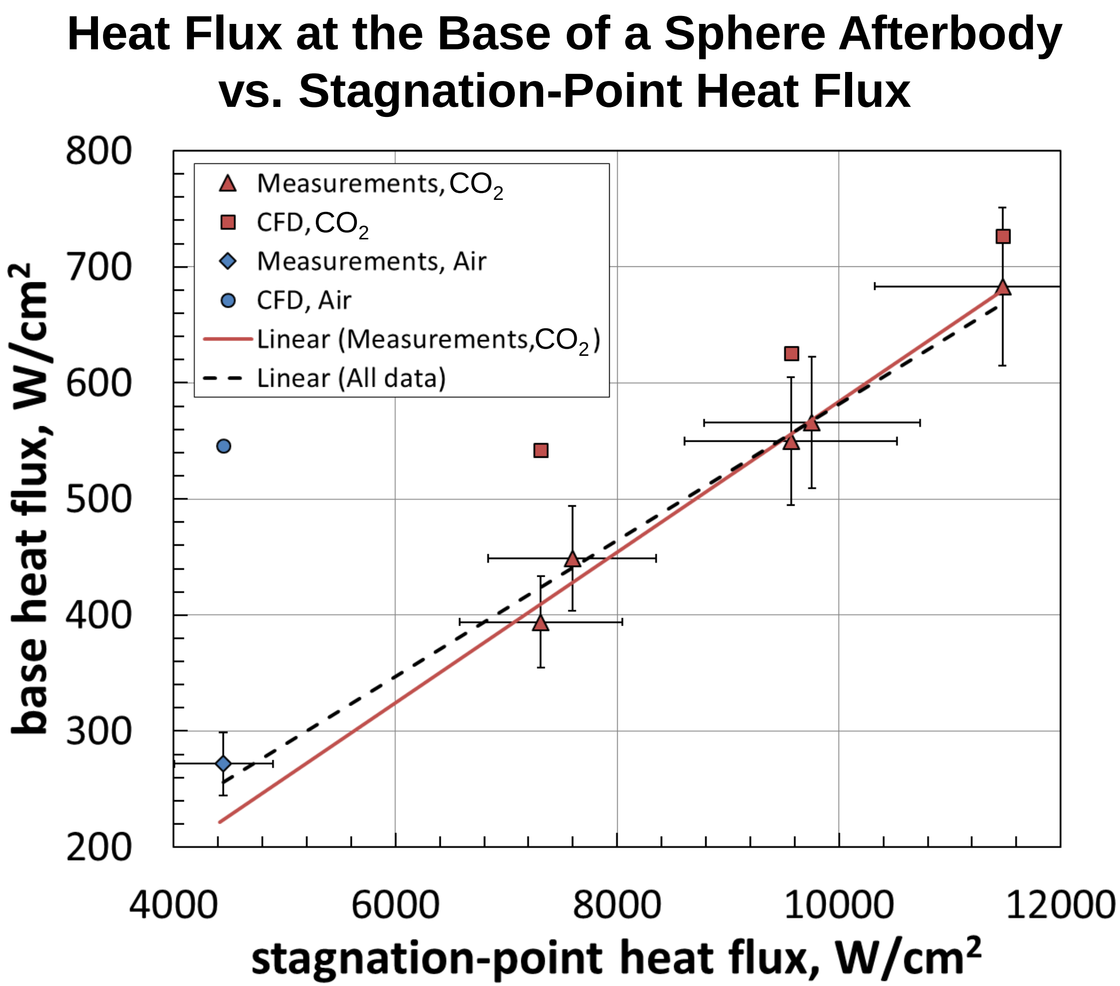
Start of Vespel Afterbody Insert

Base of Sphere

- Mean profiles averaged over 20º arc of Vespel insert
- Error bars represent ±10% of mean



Results

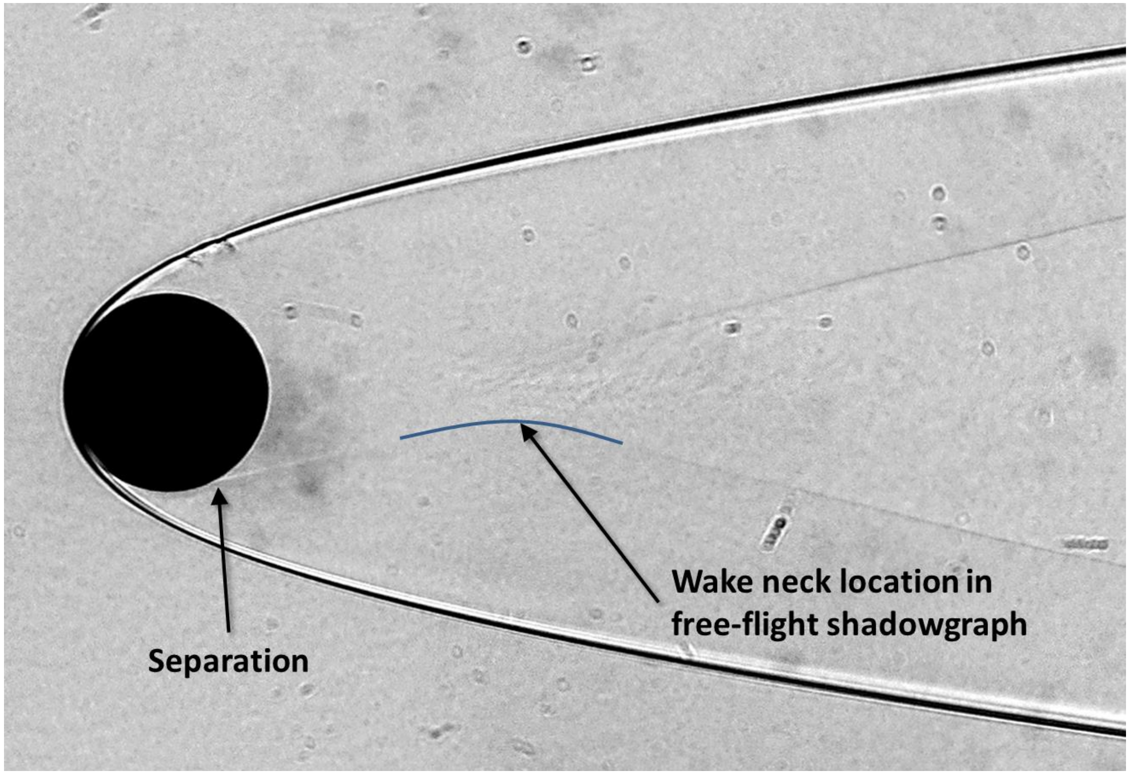


- Differences between measured and computed (assuming measured is accurate) likely indicate the limitations on using axisymmetric solutions to predict the 3D, unsteady, base-region flow
  - Axisymmetric CFD known to over-predict 3D solutions on afterbody (McDaniel, et al., *JSR*, 48/5, 2011)

Results

- **Computed flow fields had shorter wake lengths, which may account for over-prediction of heat flux at the base**

Shot 2766: test gas = CO_2 at 76 Torr, V_0 = 4.8 km/s



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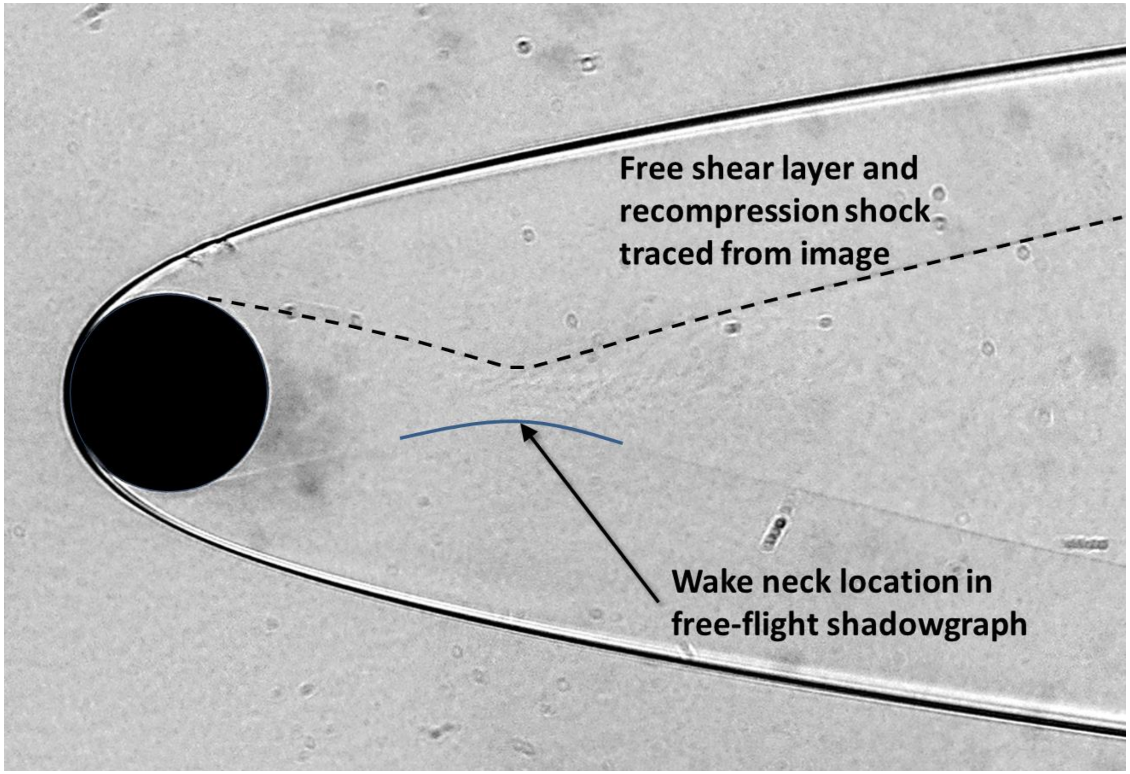

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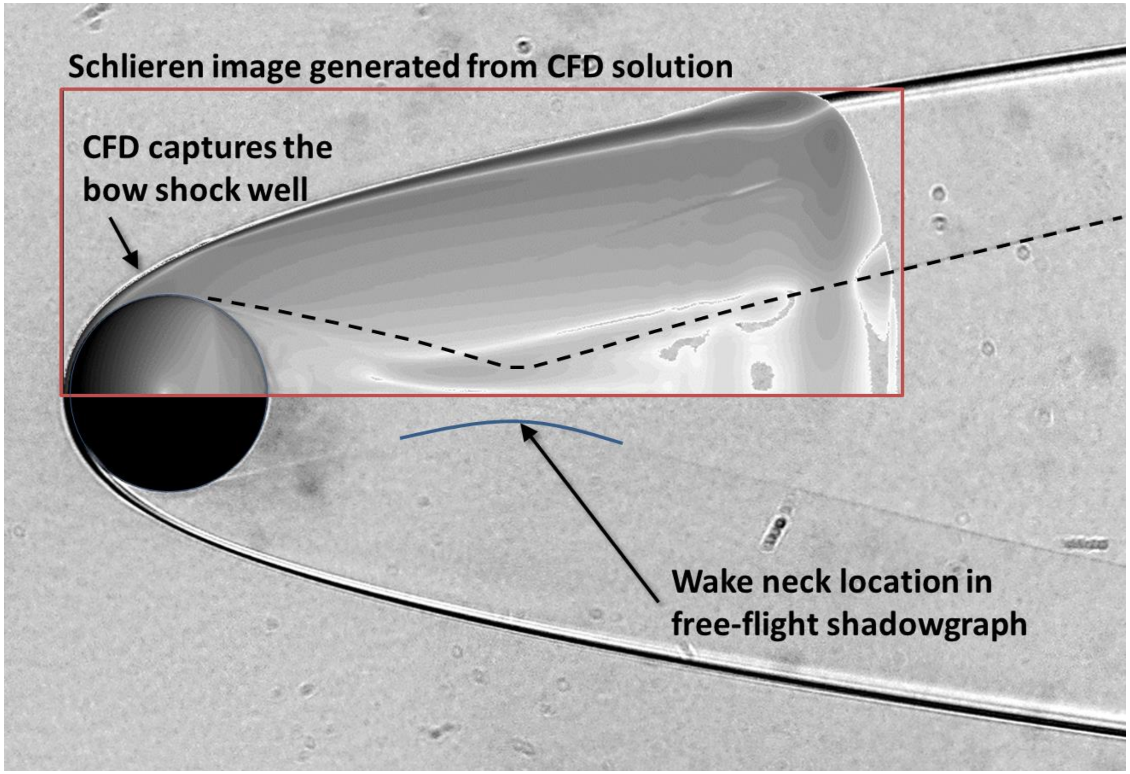

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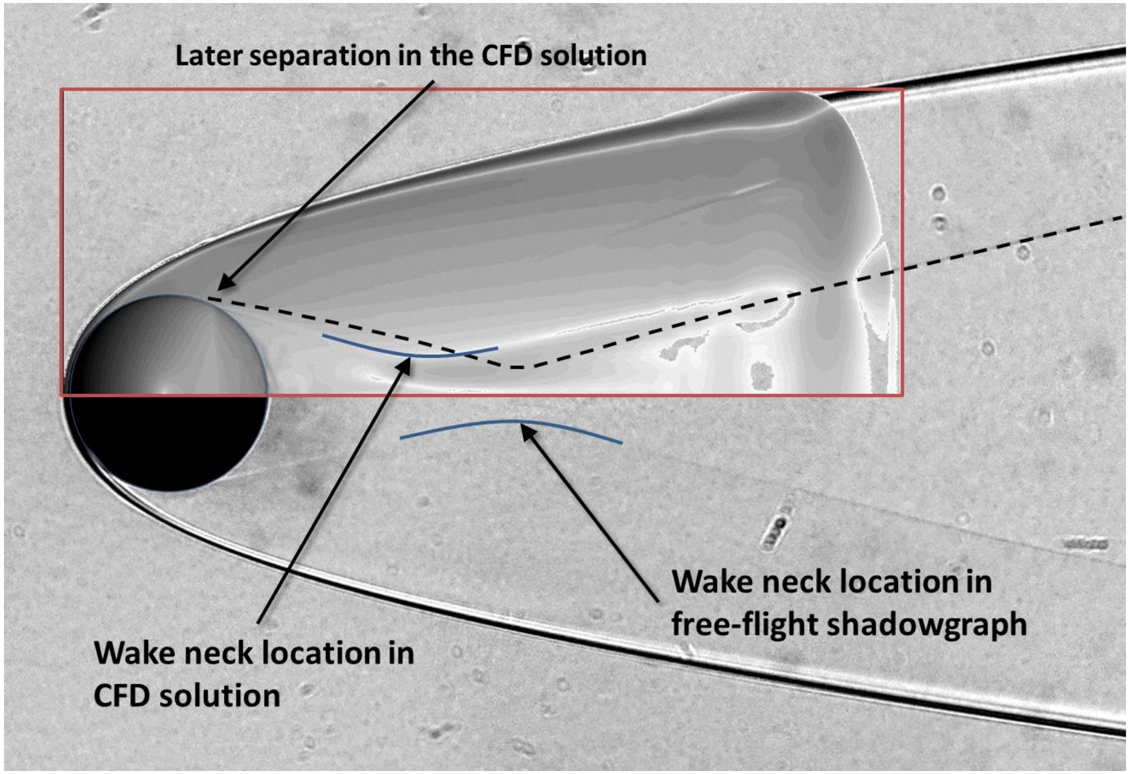
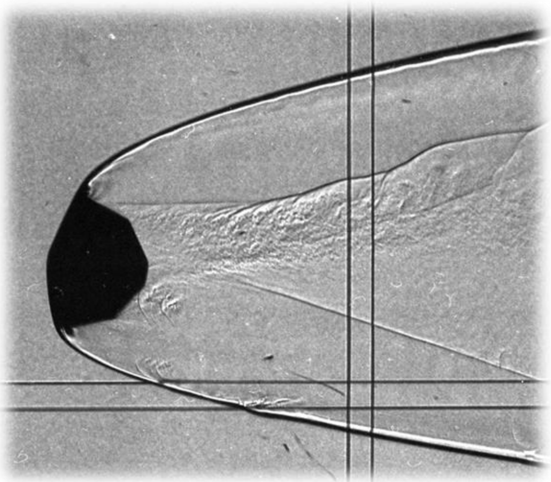


Summary

- Ames hypersonic ballistic range (HFFAF) is NASA's only remaining operational free-flight facility with a fully enclosed test section, allowing flights through practically any test gas.
- Parameters such as Mach number and Reynolds number can be varied independently
- Thermal imaging allows global measurement of surface temperatures on projectiles, from which convective heat transfer rates can be inferred
  - Examples of the measurement of heating augmentation due to surface roughness were given
- Thermal imaging technique recently demonstrated for measurements on the afterbody of spheres
  - Future steps: make measurements on an entry probe configuration, preferably, one with flight data for comparison



Acknowledgments

- Development of the afterbody measurement capability was supported by discretionary funding from the NASA Engineering and Safety Center (NESC) Passive Thermal Technical Discipline Team (TDT).
- Computational Fluid Dynamics (CFD) simulations were provided by D. K. Prabhu (forebody) and D. A. Saunders (afterbody) under the Space Technology Research and Development Contract NNA10DE12C from NASA Ames Research Center to ERC, Inc.

Source References

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Questions?